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Integrated Analysis of Interglacial Climate Dynamics (INTERDYNAMIC)

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ISSN 2191-589X ISSN 2191-5903 (electronic)
ISBN 978-3-319-00692-5 ISBN 978-3-319-00693-2 (eBook)
DOI 10.1007/978-3-319-00693-2

Library of Congress Control Number: 2014953591

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

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DFG Priority Research Program "Integrated Analysis of Interglacial Climate Dynamics" (INTERDYNAMIC)

Michael Schulz and André Paul

The research program INTERDYNAMIC aimed at a better understanding of climate dynamics using quantitative paleoclimate analyses in view of creating more reliable scenarios for future climate change. Between 2006 and 2013 a total of 22 projects were funded by the *Deutsche Forschungsgemeinschaft* (DFG) in this framework. The purpose of this book is to provide an overview of the key findings and a guide to the publications that resulted from each project.

INTERDYNAMIC was based on an integrated approach in paleoclimate research, in which all available paleoclimate archives (terrestrial and marine as well as ice cores) were combined in order to yield a comprehensive and quantitative analysis of global environmental variations. Moreover, through a close linkage between paleoclimate reconstructions and results from Earth-system models, detailed insights into the dynamics of climate variations have been gained, which are of relevance in assessing future climate changes.

The investigations in INTERDYNAMIC focused on the interglacials of the late Quaternary (including their onset and end). With respect to the global aspects of climate change, the focus in INTERDYNAMIC has been on global and continent- or basin-wide scales. Specifically, INTERDYNAMIC was directed towards the following overarching topics:

- Amplitudes of natural climate variations on timescales of several years to millennia
- Variations of patterns of climate variability in time and space

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M. Schulz and A. Paul (eds.), *Integrated Analysis of Interglacial Climate Dynamics (INTERDYNAMIC)*, SpringerBriefs in Earth System Sciences,
DOI 10.1007/978-3-319-00693-2_1

- Evidence for abrupt changes in the large-scale circulation of the Atlantic Ocean in interglacials
- Control of biogeochemical feedback mechanisms on natural limits of atmospheric concentrations of greenhouse gases
- Linkages between climate and pre-industrial cultures

These topics were addressed through a combination of climate information from paleoclimate archives with Earth-system modeling. The approach included state-of-the-art proxies and a wide spectrum of models, ranging from Earth-system models of intermediate complexity to comprehensive general circulation models.

INTERDYNAMIC consisted exclusively of collaborative, so-called Dual$^+$ projects, in which at least two of the research fields: marine archives, terrestrial archives, ice cores and Earth-system modeling were represented. Key findings from each project are summarized in the individual chapters. These are organized in terms of going from longer to shorter timescales, and from global and hemispheric to regional scales.

The first chapters compare the response to climate forcings from orbital variations and changes in atmospheric greenhouse-gas concentrations for different interglacials. Kleinen et al. (Chap. Comparison of Climate and Carbon Cycle Dynamics During Late Quaternary Interglacials) compared climate and carbon cycle dynamics during several interglacials of the late Quaternary with an emphasis of understanding the balance between terrestrial and oceanic sources and sinks during the course of the Holocene, the last interglacial (LIG), and Marine Isotope Stage (MIS) 11. Based on a global synthesis of sea-surface temperature (SST), Milker et al. (Chap. Global Synthesis of Sea-Surface Temperature Trends During Marine Isotope Stage 11) demonstrated a detectable signature of orbital forcing in the global SST pattern during MIS 11. Orbitally-driven trends in SST were investigated by Lohmann et al. (Chap. Evaluation of Eemian and Holocene Climate Trends: Combining Marine Archives with Climate Modelling) for the Holocene and LIG. Their model-data comparison indicates a shift in the seasonal imprint on proxy reconstructions that needs to be taken into account when interpreting SST reconstructions. Statistical analyses of globally distributed SST records by Mudelsee and Lohmann (Chap. Climate Sensitivity During and Between Interglacials) provided evidence that climate sensitivity during the LIG and MIS 11 were not different from the Holocene.

Onset and end of an interglacial provide valuable opportunities to test our understanding of feedback mechanisms in the climate system. It has been suggested that low-latitude warming leads ice melting in the northern hemisphere by several thousand years during the onset of interglacials. This hypothesis is challenged by Eisenhauer et al. (Chap. Phase-Shift Between Surface Ocean Warming, Evaporation and Changes of Continental Ice Volume During Termination I Observed at Tropical Ocean Sediment Cores), who identified a significant bias in low-latitude SST reconstructions that may account for the apparent offset in time. Meltwater routed through the Gulf of Mexico into the North Atlantic is thought to affect the meridional overturning circulation during glacial-to-interglacial transitions. Nürnberg et al. (Chap. Loop Current Variability—Its Relation to Meridional Overturning

Circulation and the Impact of Mississippi Discharge) question the impact of mega-discharges from the Mississippi River on the large-scale overturning circulation. Prange et al. (Chap. Hydroclimatic Variability in the Panama Bight Region During Termination 1 and the Holocene) investigated the role of atmospheric vapor transport from the Atlantic to the Pacific Ocean across Central America during the last glacial termination and find that the feedback between cross-isthmus vapor flux and the strength of the Atlantic meridional overturning circulation is negligible. Govin et al. (Chap. What Ends an Interglacial? Feedbacks Between Tropical Rainfall, Atlantic Climate and Ice Sheets During the Last Interglacial) investigated the chain of events that accompany the end of an interglacial. For the end of the LIG they find substantial shifts in the South American hydrologic cycle and upper tropical Atlantic salinities that may have affected the large-scale circulation of the Atlantic Ocean and North Atlantic climate.

Several projects addressed amplitudes of natural climate variations and changes in patterns of climate variability from a hemispheric or basin-wide perspective. Paleoceanographic reconstructions in the gateway between the Atlantic and Arctic Oceans by Spielhagen et al. (Chap. Holocene Environmental Variability in the Arctic Gateway) revealed highly variable sea-ice conditions during the Holocene. A long-term cooling trend was rapidly reversed 100 years ago and replaced by general warming in the Arctic. Morley et al. (Chap. Detecting Holocene Changes in the Atlantic Meridional Overturning Circulation: Integration of Proxy Data and Climate Simulations) addressed how climate variability at multidecadal-to-century timescales is communicated between high and low latitudes. They demonstrated an important role of central-water circulation in the North Atlantic Ocean to transfer regional climate signatures of various forcings (freshwater flux, solar variability, orbital parameters) to a hemispheric or global scale. On multidecadal and millennial time-scales, precipitation variability in the Caribbean region during the Holocene was strongly linked to SST changes in the North Atlantic Ocean, namely the Atlantic Multidecadal Oscillation and variations in the strength of the Atlantic Meridional Overturning Circulation (Felis et al., Chap. Control of Seasonality and Interannual to Centennial Climate Variability in the Caribbean During the Holocene—Combining Coral Records, Stalagmite Records and Climate Models). For the westerlies in the southern hemisphere Lamy et al. (Chap. The Southern Westerlies During the Holocene: Paleoenvironmental Reconstructions from Chilean Lake, Fjord, and Ocean Margin Sediments Combined with Climate Modeling) revealed a distinct latitudinal anti-phasing of wind changes between the core and northern margin of the wind belt over the Holocene on centennial-to-millennial timescales. Changes in atmospheric transport were also found to be relevant by Wegner et al. (Chap. Mineral Dust Variability in Antarctic Ice for Different Climate Conditions) to account for variations in dust transport to Antarctica on glacial-to-interglacial timescales.

Changes in the hydrological cycle have been studied in several projects across a range of timescales and regions. For the Indian monsoon system, Schneider et al. (Chap. Model-Data Synthesis of Monsoon Amplitudes for the Holocene and Eemian) reconstructed similar conditions for the Holocene and the LIG, whereas climate-model simulations indicate a more intense hydrological cycle for the LIG.

For the Asian monsoon system, Dallmeyer et al. (Chap. Vegetation, Climate, Man—Holocene Variability in Monsoonal Central Asia) found that the atmospheric response to Holocene insolation forcing was strongly modified by ocean-atmosphere interactions, while the interaction between vegetation and atmosphere had only minor influence on the large-scale Holocene climate change and was only important at a regional level. Hydrological changes in northwest Africa during the Holocene were studied by Schefuß et al. (Chap. North-West African Hydrologic Changes in the Holocene: A Combined Isotopic Data and Model Approach), who found no evidence for an abrupt change at the end of the African humid period suggesting a gradual precipitation decline. Linkages between climate and pre-industrial cultures were evaluated by Lemmen et al. (Chap. Global Land Use and Technological Evolution Simulations to Quantify Interactions Between Climate and Pre-industrial Cultures) for the Holocene transition to agriculture in western Eurasia. It was shown that migration is not a necessary prerequisite for this transition and that climate variability and extreme events had no significant impact, which reflects societal resilience.

Several regional studies were carried out in the framework of INTERDYNAMIC. Interactions between climate variations, biogeochemical cycles, and ecosystem variability have been studied in the Eastern Mediterranean Sea during the formation of Sapropel S1 in the Holocene. Schmiedl et al. (Chap. Holocene Climate Dynamics, Biogeochemical Cycles and Ecosystem Variability in the Eastern Mediterranean Sea) provide evidence for a scenario, in which sufficient organic matter for sapropel formation was buried under oligotrophic conditions in an anoxic water column, hence refuting the "high-productivity" hypothesis. Environmental and climate changes during the last two glacial terminations and interglacials have been studied by Arz et al. (Chap. Environmental and Climate Dynamics During the Last Two Glacial Terminations and Interglacials in the Black Sea/Northern Anatolian Region) in the Black Sea and northern Anatolian region. Holocene and LIG developed differently, with warmer and moister conditions prevailing during the LIG. Furthermore, major fluctuations in the hydrological state of the Black Sea were closely linked to changes in the terrestrial environment. Reconstructions of summer precipitation variability and flood events for the Main region in southern Germany by Schoenbein et al. (Chap. Seasonal Reconstruction of Summer Precipitation Variability and Dating of Flood Events for the Millennium Between 3250 and 2250 Years BC for the Main Region, Southern Germany) revealed a noticeable excursion towards drier conditions around 2750 BC. In addition, a period of high flood frequency from 2991 BC to 2693 BC has been identified. The evolution of precipitation and its variability over Europe and the Mediterranean over the last two millennia was investigated by Gomez-Navarro et al. (Chap. Precipitation in the Past Millennium in Europe—Extension to Roman Times), who demonstrated the added value of regional climate models for downscaling. As a result, the Medieval Climate Anomaly was characterized by periods with warmer and drier summer conditions, and the Little Ice Age was characterized by periods with colder and wetter summer conditions, respectively.

In addition to the scientific achievements, INTERDYNAMIC provided a platform that facilitated the exchange of knowledge in the German paleoclimate community and linked their activities with international programs and projects. By training a large number of young scientists, the program has also helped to create a new generation of paleoclimatologists with a great awareness of adjacent disciplines. To this end, the Dual$^+$ concept of combining different expertise in a project right from its start has proven very useful. Specifically, the exchange between scientists reconstructing past climate changes and scientists numerically modeling past climate changes has benefitted greatly from INTERDYNAMIC.

Acknowledgements We thank the DFG for generously supporting INTERDYNMIC over a 6-year period. We are grateful to the anonymous mid-term reviewers, who helped to shape the program.

Comparison of Climate and Carbon Cycle Dynamics During Late Quaternary Interglacials

Thomas Kleinen, Elena Bezrukova, Victor Brovkin, Hubertus Fischer, Steffi Hildebrandt, Stefanie Müller, Matthias Prange, Rima Rachmayani, Jochen Schmitt, Robert Schneider, Michael Schulz and Pavel Tarasov

Abstract Within the project COIN we investigated climate and carbon cycle changes during late Quaternary interglacials using ice core and terrestrial archives, as well as earth system models. The Holocene carbon cycle dynamics can be explained both in models and data by natural forcings, where the increase in CO_2 is due to oceanic carbon release, while the land is a carbon sink. Climate changes during MIS 11.3 were mainly driven by insolation changes, showing substantial differences within the interglacial. Terrestrial reconstructions and model results agree, though data coverage leaves room for improvement. The carbon cycle dynamics during MIS 11.3 can generally be explained by the same forcing mechanisms as for the Holocene, while model and data disagree during MIS 5.5, showing an increasing CO_2 trend in the model though reconstructions are constant.

Keywords Interglacial · Carbon cycle · $\delta^{13}CO_2$ · Holocene · MIS 11.3 · MIS 5.5 · Ice core data · Terrestrial data · Earth system model · CO_2

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M. Schulz and A. Paul (eds.), *Integrated Analysis of Interglacial Climate Dynamics (INTERDYNAMIC)*, SpringerBriefs in Earth System Sciences,
DOI 10.1007/978-3-319-00693-2_2